

Strength performance of mortise and loose-tenon furniture joints under uniaxial bending moment

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Abstract: We determined the effects of adhesive type and loose tenon dimensions (length and thickness) on bending strength of T-shaped mortise and loose-tenon joints. Polyvinyl acetate (PVAc) and two-component polyurethane (PU) adhesives were used to construct joint specimens. The bending moment capacity of joints increased significantly with increased length and thickness of the loose tenon. Bending moment capacity of joints constructed with PU adhesive was approximately 13% higher than for joints constructed with PVAc adhesive. We developed a predictive equation as a function of adhesive type and loose tenon dimensions to estimate the strength of the joints constructed of oriental beech (*Fagus orientalis* L.) under uniaxial bending load.

Keywords: bending moment capacity, mortise and loose tenon, loose tenon dimensions, polyvinyl acetate, two-component polyurethane

Introduction

It is generally accepted that the structural integrity of furniture depends more on joint design than on any other factor (Eckelman 2003). Given that joints are ordinarily weaker than the members they join together, good design practice dictates that joints be designed to develop their maximum load capacity. Information is needed that will enable designed joints to meet specified engineering requirements consistent with anticipated end-use requirements. Study of the strength performance of furniture joints has traditionally been considered necessary in research on wood and wood products (Eckelman and Haviarova, 2011; Eckelman et al. 2004; Erdil et al. 2005; Haviarova et al. 2001a and 2001b;

Simek et al. 2010; Smardzewski and Papuga 2004; Tas 2010).

Tankut and Tankut (2005) demonstrated that width and geometric shape of tenons, and glue line thickness have significant effects on the strength of mortise and tenon joints. Erdil et al. (2005) reported that the stiffness of mortise and tenon joints increased with increasing length or depth of tenons. In the case of round mortise and tenon joints, Eckelman et al (2006a) demonstrated that close-fitting shoulders substantially increased the strength of the joint.

The mortise and loose-tenon is a new type of furniture joint that is similar to the conventional mortise and tenon joint. The main difference between these two kinds of furniture joints is that in mortise and loose-tenon joints, the tenon is prepared separately from the horizontal and vertical members. The loose tenon joints can be more efficient and economical than mortise and tenon joints. For example, the ends of members such as rails are not sculpted to form tenons, unlike the mortise and tenon joint, and this reduces material costs due to use of woods with smaller dimensions. Joint production time and ease of manufacture are comparable with those for dowel joints. Mortises for loose tenon joints can be made using simple machines and can even be constructed using hand drills (Aman et al. 2008). Aman et al (2008) compared the bending moment capacities of dowel, mortise and loose-tenon, and conventional mortise and tenon joints constructed of three wood species, namely, black cherry (*Prunus serotina*), red oak (*Quercus* Spp.), and sugar maple (*Acer saccharum*). These researchers found that the bending moment capacity of loose tenon joints was between that of a dowel joint and a conventional mortise and tenon joint.

The goal of our study was to identify factors that affect strength performance of mortise and loose-tenon joints. We carried out tests to determine the effects of adhesive type and loose tenon dimensions (length and thickness) on the bending moment capacity of mortise and loose tenon furniture joints.

Materials and methods

Joints members were constructed of oriental beech (*Fagus ori-*

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entalis L.), because this is a widely used wood species in Middle East countries. Configuration and dimensions of T-shaped mortise and loose tenon joints used in the study are shown in Fig. 1. Mortises were cut in the rail (horizontal) and post (vertical) members of joints using a standard mortising jig (Derikvand 2011). The thickness of the rounded-edge loose tenon amounted to $6^{-0.1}$ and $8^{-0.1}$ mm. The clearance between the loose tenon and side walls of the mortise was nominally 0.05 mm. To achieve this quality of fit, in the side walls of the mortise, the width of the loose tenon was quit equal to the length of the mortise (50 mm), so that the loose tenon could not easily move into the mortise. As shown in Fig. 1, the length of the loose tenon amounted to $30^{-0.25}$, $45^{-0.25}$, $60^{-0.25}$, and $90^{-0.25}$ mm in such a way that the penetration depth of the loose tenon in the post and rail members was nominally 15, 22.5, 30, and 45 mm. Polyvinyl acetate (PVAc) and two-component polyurethane (PU) adhesives were used to construct joint specimens for strength testing (Table 1). Before assembling and in order to isolate shoulders, a piece of wax paper was included between the end of the rail member and the face of the post member. In the first set of experiments, 8 combinations were designed to determine the effect of loose tenon length and adhesive type on the bending moment capacity of joints. Loose tenon thickness was held constant at 6 mm while the loose tenon penetration depth in the post and rail amounted to 15, 22.5, 30, and 45 mm. In the second set of experiments, with the exception of the loose tenon thickness, all variables were the same as in the first set of experiments. The loose tenon thickness in the second set of experiments was 8 mm. Test specimens included 16 combinations, regarding adhesive type, loose tenon length, and loose tenon thickness. Five replicates were constructed for each combination. Joints were then conditioned at a relative humidity of $65\% \pm 3\%$ at $20^\circ\text{C} \pm 2^\circ\text{C}$ for a month (Maleki et al. 2012). Finally, using a standard testing jig (Fig. 2), 80 joint specimens were tested on a computer-controlled Instron (4486) test machine. Loading rate was 5 mm/min during the tests. Bending moment capacity of the joints, M (N·m), was calculated by the following equation: $M = FL$, where, F (N) is the ultimate load and L (m) is the moment arm; 35 cm.

Table 1: Technical properties of adhesives

| Adhesive type | Shear strength (MPa) | Color | Hardener | Density (gr/cm ²) | Viscosity (cP) | Assembly time (min) | Application temperature | Water resistance |
|--------------------------|----------------------|-------|----------------------|-------------------------------|----------------|---------------------|-------------------------|------------------|
| Polyvinyl acetate (PVAc) | 14.5 | White | None | 1.073 | 45000±5000 | 15±2 | 5–40°C | None |
| Polyurethane (PU) | 16.75 | Cream | MDI 418 ^a | 1.3 | Not indicated | 30 | 5–45°C | Water proof |

a: Polymeric MDI (Methylene diphenyl isocyanate)

Results

Average values of the ultimate bending moment capacity of the joints along with Duncan test results for determination of differences between groups are given in Table 2.

The difference between groups was highly significant in terms of adhesive type, loose tenon length, and loose tenon thickness

Analysis of variance (ANOVA) was performed to quantify differences between variables. The Duncan test was used to quantify differences between the groups.

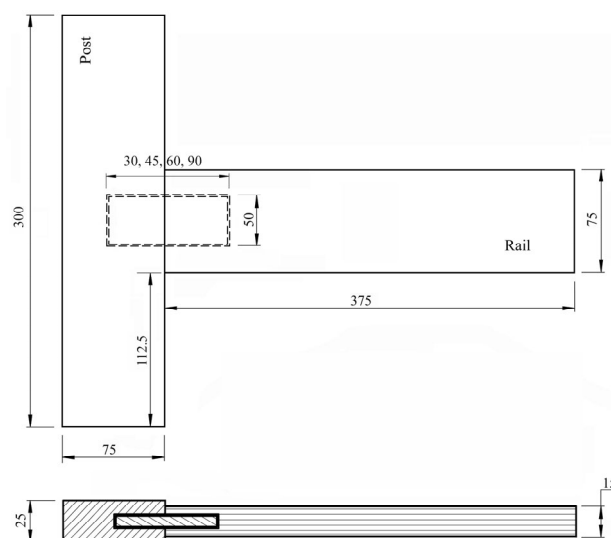


Fig. 1: Configuration and dimensions (mm) of joints

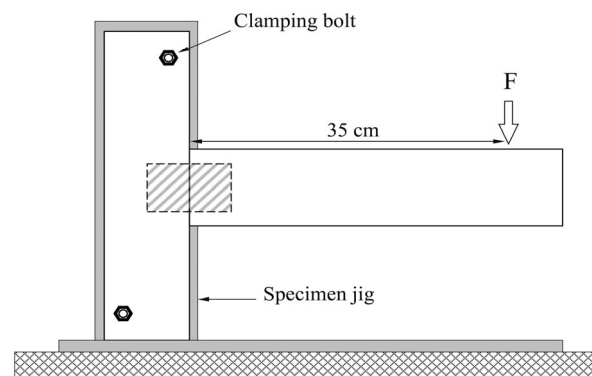


Fig. 2: Testing set up

(Table 3). With the exception of the group (Tenon length \times Tenon thickness), the interactions between groups were not statistically significant ($p < 0.05$).

There was no significant difference between groups in terms of triple interaction.

In the case of joints constructed with PVAc adhesive, the increase in the length of the loose tenon from 15 mm to 22.5 mm increased the bending moment capacity of joints by 29%, while a similar increase in the loose tenon length from 22.5 mm to 30

mm caused increase of joint strength by approximately 35.5%. In addition, following the increase in loose tenon length from 30 to 45 mm the bending moment capacity of the joints increased by 22%. In the case of joints constructed with PU adhesive, the increases in the loose tenon length from 15 to 22.5 mm, 22.5 to 30 mm, and 30 to 45 mm caused increases in joint strength of 30%, 41.5% and 22%, respectively. The bending moment capacity of joints constructed with PU adhesive was, on average, 12.2% higher than recorded for joints constructed with PVAc adhesive. However, Duncan test results showed that there were no significant differences in the bending moment capacity of comparable joints constructed with PU and PVAc adhesives at loose tenon lengths of 15 and 22.5 mm.

Table 2: Average values of observed and predicted bending moment capacity of joints

| Adhesive type | Tenon thickness (mm) | Tenon depth (mm) | Actual bending moment (N·m) | COV (%) | Duncan groups | Predicted bending moment ^a (N·m) | Differences (%) |
|---------------|----------------------|------------------|-----------------------------|---------|---------------|---|-----------------|
| PVAc | 6 | 15 | 174.74 | 14.03 | F | 176.76 | + 1.14 |
| | | 22.5 | 225.76 | 10.37 | DE | 233.33 | + 3.24 |
| | | 30 | 305.59 | 6.08 | C | 285.61 | - 7.13 |
| | | 45 | 373.59 | 11.05 | B | 382.56 | + 2.34 |
| PU | 6 | 15 | 190.21 | 7.46 | EF | 199.60 | + 4.70 |
| | | 22.5 | 246.89 | 13.41 | D | 263.47 | + 6.29 |
| | | 30 | 349.40 | 8.91 | B | 322.51 | - 8.33 |
| | | 45 | 425.46 | 9.57 | A | 431.99 | + 1.51 |
| PVAc | 8 | 15 | 246.04 | 11.85 | F | 247.42 | + 0.56 |
| | | 22.5 | 311.57 | 13.82 | E | 323.35 | + 3.64 |
| | | 30 | 408.59 | 11.69 | D | 393.01 | - 3.96 |
| | | 45 | 516.94 | 5.83 | B | 521.21 | + 0.82 |
| PU | 8 | 15 | 261.20 | 14.04 | F | 279.39 | + 6.51 |
| | | 22.5 | 378.80 | 11.13 | D | 365.13 | - 3.74 |
| | | 30 | 461.02 | 8.65 | C | 443.79 | - 3.88 |
| | | 45 | 576.38 | 4.82 | A | 588.55 | + 2.07 |

^a Regression expression: $M = 0.19 \times (L^{0.46} \times Th^{0.75}) \times (L^{0.46} + Th^{0.75}) \times S^{0.84}$

Table 3: Results of ANOVA for amounts of bending moment capacity of joints

| Source (symbol) | Sum of squares | df | Mean square | F | Sig. |
|---------------------|----------------|----|-------------|---------|-------|
| Glue (A) | 33243.858 | 1 | 33243.858 | 30.143 | 0.000 |
| Tenon length (B) | 734195.619 | 3 | 244731.873 | 221.906 | 0.000 |
| Tenon thickness (C) | 235727.185 | 1 | 235727.185 | 213.741 | 0.000 |
| A * B | 4662.070 | 3 | 1554.023 | 1.409 | 0.248 |
| A * C | 1215.241 | 1 | 1215.241 | 1.102 | 0.298 |
| B * C | 14450.382 | 3 | 4816.794 | 4.368 | 0.007 |
| A * B * C | 1614.273 | 3 | 538.091 | 0.488 | 0.692 |
| Error | 70583.335 | 64 | 1102.865 | | |
| Total | 10386445.260 | 80 | | | |

R squared = 0.936 (Adjusted R Squared = 0.920)

In the second set of experiments, in the case of joints con-

structed with PVAc adhesive, the increase in the length of the loose tenon from 15 to 22.5 mm increased the joint strength by 26.6%, while the increase in the loose tenon length from 22.5 to 30 mm caused increase in joint strength of approximately 31%. The increase in loose tenon length from 30 to 45 mm increased the strength of the joints by 26.5%. In the case of joints constructed with PU adhesive, increase in loose tenon length from 15 to 22.5 mm, 22.5 to 30 mm, and 30 to 45 mm caused increase in joint strength by 45%, 21.7% and 25%, respectively.

Overall, the bending moment capacity of joints constructed with PU adhesive was 13.1% higher than for joints constructed with PVAc adhesive. Duncan test results showed that, except in joints with 15 mm tenon length, there were no significant differences in the bending moment capacity of comparable joints at loose tenon lengths of 22.5, 30, and 45 mm.

In general, the bending moment capacity of joints with loose tenon thickness of 8 mm was approximately 38% higher than for joints constructed with 6 mm loose tenon thickness.

Discussion

The bending moment capacity of joints significantly increased with the increase in the length and thickness of the loose tenon. These results for mortise and loose tenon joints are in agreement with those reported for mortise and tenon joints by Eckelman et al. 2006, Erdil et al. 2005, Tankut and Tankut 2005.

The type of adhesive used in constructing the joint specimens also had a highly significant effect on the strength of joints. Erdil et al. (2005) found the same results for the effect of adhesive type on bending moment capacity of rectangular mortise and tenon joints.

Most joint failures occurred in the adhesive line between the loose tenon and the walls of the mortise. In this case, it can be said that the shear strength of adhesive used in constructing joint specimens was the determinant factor on the bending moment capacity of joints.

This interpretation would be confirmed if a non-linear regression analysis were conducted on the data set. For example, the following regression expression, as function of the tenon length and tenon thickness, can be used to estimate bending moment capacity of such joints:

$$M = a_0 \times (L^{a_1} \times Th^{a_2}) \times (L^{a_1} + Th^{a_2}) \quad (1)$$

where, M is bending moment capacity, N.cm; L is tenon length, mm; Th refers to thickness of tenon, mm; and a_0 , a_1 , and a_2 are regression coefficients.

When this expression was fitted to the data, the following expression was obtained:

$$M = 1.94 \times (L^{0.46} \times Th^{0.75}) \times (L^{0.46} + Th^{0.75}) \quad (2)$$

with $R^2 = 88.72\%$.

Overall, differences between observed and predicted values, on average, were 6.05% and the largest differences between ob-

served and predicted values were -10%, -10.22%, and -15%.

If the term of shear strength of adhesive is included in expression (1), so that:

$$M = a_0 \times (L^{a1} \times Th^{a2}) \times (L^{a1} + Th^{a2}) \times S^{a3} \quad (3)$$

and a regression analysis conducted on the results, the following result is obtained:

$$M = 0.19 \times (L^{0.46} \times Th^{0.75}) \times (L^{0.46} + Th^{0.75}) \times S^{0.84} \quad (4)$$

with $R^2 = 92.17\%$, where, S refers to adhesive shear strength.

In this case, mean differences between observed and predicted values were less than 3.75%, and the largest differences between observed and predicted values were approximately -7% and -8% (Table 3).

These results indicate that the type of adhesive had a tangible effect on the bending moment capacity of mortise and loose tenon joints. The intensity of this relationship is likely to vary by wood species (Table 4).

Table 4: Shear strength of PVAc and two-component PU adhesives in different wood species (Derikvand et al, unpublished).

| Adhesive type | Wood species | Shear strength (MPa) |
|---------------|--------------|----------------------|
| PVAc | Beech | 14.50 |
| | Walnut | 11.88 |
| | Oak | 11.07 |
| | Sycamore | 11.00 |
| | Poplar | 10.19 |
| PU | Fir | 7.34 |
| | Beech | 16.75 |
| | Walnut | 15.14 |
| | Oak | 15.56 |
| | Sycamore | 11.46 |
| | Poplar | 9.52 |
| | Fir | 8.42 |

Conclusion

We investigated the effects of adhesive type and loose tenon dimensions on bending moment capacity of T-shaped mortise and loose-tenon joints. The following conclusions can be drawn from our results:

(1) Bending moment capacity of mortise and loose tenon joint depended on the type of adhesive and the dimensions of loose tenon.

(2) Bending moment capacity of mortise and loose tenon joint increased significantly with increased thickness and length of the loose tenon.

(3) Bending moment capacity of mortise and loose tenon joints constructed with two-component PU adhesive was 13% greater than for joints fabricated with PVAc adhesive.

(4) Bending moment capacity of mortise and loose tenon joint constructed of oriental beech may be predicated using the non-linear regression expression:

$$M = 0.19 \times (L^{0.46} \times Th^{0.75}) \times (L^{0.46} + Th^{0.75}) \times S^{0.84} \quad (5)$$

where, M is bending moment capacity, N.cm; L is tenon length, mm; Th refers to thickness of tenon, mm; and S is shear strength of the adhesive, MPa.

The above regression equation was derived using limited numbers of experiments and its accuracy for joints constructed of other wood species should be tested in future studies. Likewise, in order to obtain a comprehensive formula, the predictive equation should be developed using other factors affecting the bending moment capacity of mortise and loose tenon joints, such as tenon width, tenon thickness, shoulder width and wood species.

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